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National Aeronautics
and Space Administration

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SUMMARY

An investigation was conducted to obtain thermal conductivity (TC) data for tungsten-fiber-reinforced superalloys (TFRS). To do so, a thermal-conductivity comparator apparatus and technique were developed for determining the TC of small, thin specimens that simulate the thin walls of a turbine blade. The TC's measured with this apparatus were within 10 percent of a National Bureau of Standards sample calibration. The thermal-conductivity comparator was used to determine the TC's of five materials at temperatures from 500 to 900 K.

The TC relationship with temperature was determined for FeCrAlY, Alloy-3 (a NASA-developed nickel-base alloy), a stainless-steel reference material from the National Bureau of Standards, and two tungsten-fiber-reinforced superalloy composite materials. The two composites were 50-volume-percent-tungsten uniaxially reinforced FeCrAlY and 65-volume-percent-tungsten uniaxially reinforced Alloy-3. For the FeCrAlY composite, TC was measured in the transverse direction (perpendicular to the fibers); and for Alloy-3 composite, it was measured in the longitudinal direction (parallel to the fibers).

The composite TC data were compared with existing TC data for MAR-M200, a high-strength nickel-base superalloy, and were significantly higher in both the transverse and longitudinal directions. The longitudinally measured TC of the 65-volume-percent TFRS (Alloy-3) was 3 to 5 times the TC of MAR-M200, depending on temperature. The transversely measured TC of the 50-volume-percent TFRS (FeCrAlY) was 1.5 to 2 times the TC of MAR-M200. The TC data for the matrix materials, Alloy-3 and FeCrAlY, were approximately the same and ranged from 9 to 22 watts per meter kelvin (W/m · K) at temperatures from 500 to 900 K.

INTRODUCTION

Metal-matrix composites have many properties that make them attractive for aircraft turbine-engine applications. Cost-benefit analyses have shown that increasing the turbine blade use-temperature can significantly improve engine performance. The increased-use-temperature potential of tungsten-fiber-reinforced superalloys (TFRS) has been recognized and studied for some time at the NASA Lewis Research Center (ref. 1). Thus, TFRS, which have excellent high-temperature strength, are being considered as materials for high-temperature turbine blades. Because of the high-temperature

strength of TFRS, turbine designers could improve engine performance by increasing the turbine-inlet gas temperature while keeping the cooling airflow at current levels or by keeping the turbine-inlet gas temperature at current levels while lowering the cooling airflow.

Thermal-conductivity data for TFRS are needed for evaluating the relative merits of these emerging materials for turbine blade applications. Since such TC data are not available in the literature, experimental techniques to obtain the data were sought. Reported techniques for measuring TC are not well adapted to the thin-sheet TFRS specimens that most nearly simulate turbine blade walls. Thus, an experimental technique for measuring the TC of thin-sheet specimens was developed and is described herein. Thermal-conductivity data for two representative TFRS composites and two matrix materials were obtained with this technique.

MATERIALS AND SPECIMEN PREPARATION

In this study we measured the TC of five materials: unreinforced FeCrAlY, W/FeCrAlY composite, unreinforced Alloy-3, W/Alloy-3 composite, and 735-M1 stainless steel. The materials investigated and their nominal chemical composition in weight percent were as follows:

(1) Unreinforced FeCrAlY matrix material - 23Cr-5Al-1Y-Fe (bal.)

(2) W/FeCrAlY composite - 50-volume-percent, 0.038-centimeter-diameter W-1ThO_2 wire in FeCrAlY

(3) Unreinforced Alloy-3 matrix material - 15Cr-25W-2Al-2Ti-Ni (bal.)

(4) W/Alloy-3 composite - 65-volume-percent, 0.038-centimeter-diameter, cleaned and straightened (CS) tungsten-218 wire in Alloy-3

(5) Stainless-steel reference material - 735-M1 obtained from the National Bureau of Standards (NBS)

Tungsten alloy 218CS is an unalloyed, doped, tungsten lamp fiber that has been cleaned and straightened. Tungsten alloy W-1ThO_2 is a lamp fiber containing a dispersed oxide phase. Both fibers were heavily worked.

Both composites were unidirectionally reinforced. The W-1ThO_2/FeCrAlY composite was fabricated into sheet 0.127 centimeter thick containing 50 volume percent of tungsten fibers that were 0.038 centimeter in diameter. The fabricating technique involved hot pressing stacked layers of matrix alloy and tungsten fiber (ref. 2). The unreinforced FeCrAlY specimen material was fabricated into sheet 0.104 centimeter thick by hot pressing layers of powder cloth. The thickness range for these two materials (0.104 to 0.127 cm) is close to the wall thickness at the root of some advanced convection-cooled turbine blade airfoils. Both the composite and unreinforced materials

were cut into circular TC specimens 1.27 centimeters in diameter. A typical transverse W/FeCrAlY TC specimen after fabrication is shown in figure 1.

The unreinforced Alloy-3 and W/Alloy-3 composite TC specimens were cut from bars. A cross section of a typical longitudinal W/Alloy-3 TC specimen is shown in figure 2. The composite bars were fabricated by slip casting nickel alloy powders into metal tubes that contained tungsten fibers and then subjecting the tubes to isostatic hot pressing (ref. 3). Both specimens measured 1.27 centimeters in diameter by 0.381 centimeter thick. The 218CS W/Alloy-3 composite specimens contained 65 volume percent of tungsten fibers with the fibers alined parallel to the axis of the cylindrical specimens.

The standard reference material was a bar of 735-M1 stainless steel 1.27 centimeters in diameter and 15 centimeters long. This material was purchased from the National Bureau of Standards, who certified its TC properties from room temperature to 1200 K. Sections of this bar, the same thickness as the test specimens, were carefully removed with an abrasive cutoff wheel.

APPARATUS

A literature survey of experimental methods to measure TC revealed two problems with existing techniques. First, our samples were smaller and thinner than the optimum sample. Second, we lacked a means to very accurately measure the heat that was passing through the sample. A technique to determine TC for small samples was developed to overcome both these problems. The apparatus and procedure for this technique are described in this and the following section.

The measuring apparatus (fig. 3) was a column consisting of the NBS reference samples, the specimen, spacers, and end caps held firmly between a copper heat-source (heating) bar and a copper heat-sink (cooling) bar. The heat that passed axially through the test specimen was measured by using the calibrated NBS reference samples that had been placed on either side of the test specimen. The radial heat transfer was assumed to be negligible, and the axial heat transfer through the test specimen was taken as the average of the heat passing through the NBS reference samples. The NBS reference samples and the test specimen were separated by thin copper spacers of the same diameter as the specimens. Copper was used for the spacers and the heating and cooling bars because of its high thermal conductivity. The heating and cooling bars were larger in diameter than the column in order to create an air gap between the column and the mica sheet and alumina insulating sleeve assembly. The air gap and insulating sleeve caused the radial heat transfer from the sides of the column to be uniform along the column length.

The temperatures of the circular face of each NBS reference sample and the specimen were measured with Chromel-Alumel thermocouples carefully spot welded to each surface, as shown in figure 3. The two wires making up each thermocouple were separated and spot welded individually to the sample surface, as recommended in reference 4 for measuring an isothermal surface. The thin copper spacers had flat parallel sides and two thin slots that were approximately twice the width of the individual thermocouple wires. The slots in the spacers allowed them to fit over the individual thermocouple wires. Braided glass sleeves were used to insulate the individual thermocouple wires from the copper spacers and the specimen surface. All the thermocouples were connected to a constant-temperature thermoelectric cold junction that was in turn connected to a potentiometer, as shown schematically in figure 3. A constant load of about 90 newtons was applied to the column while TC data were being taken. The load was applied with a strong spring, with a spring constant of 29 000 newtons per meter, and a suitable vise. The vise was adjusted at each new temperature to keep the spring compression constant. In this experiment, the error in the thermocouple measurement system was estimated to be 0.3 kelvin.

The necessity of intimate interface contact between the disks dictates that all disk surfaces be smooth and parallel. A smooth surface finish was produced on all specimen surfaces by using 600-grit silicon carbide paper. The spacers and all specimens had parallel faces, with the spacers being kept as thin as possible. Lines were scribed onto the NBS reference samples and the specimen faces by using the spacer slots as a template. Then the individual thermocouple wires were spot welded in the center of these scribed lines. Next, the spacers were fitted over the thermocouples; and the NBS reference samples, the specimens, and the spacers were butted against each other. An additional spacer and disk of stainless steel was placed on each end of the column in order to eliminate any nonlinear end effects and to ensure a steady-state axial heat flow through the central part of the assembly. This assembly then formed a column, as shown in figure 3.

This TC measurement technique has certain limitations. The operating temperature of the experiment, as described, was limited to the softening point of copper; also, since the experiments were done in air, the operating temperature was limited by the amount of oxide formed at the specimen-spacer interface. For these reasons, no data were obtained above 900 K. It was imperative that the column be prepared for the TC determination by developing good metal-to-metal bonds at all the interfaces. An initial load of about 120 newtons was applied to the column while the entire column was being heated with a torch to approximately 900 K. This process slightly deformed the spacers and also ensured the uniform contact at all the interfaces necessary for good heat transfer. After several minutes at 900 K, the column was cooled to room temperature in preparation for the TC experiment described next.

PROCEDURE

The TC data were obtained as follows: With the column assembled and spring loaded in the clamping device, heat was applied to the copper heating bar by a torch or a resistance-heated furnace while the copper cooling bar at the opposite end of the column was being air cooled. This arrangement produced a temperature gradient through the column. The temperature gradient of the column initially varied with time but reached equilibrium within 30 minutes. The temperatures of each surface of both the NBS reference samples and the test specimen were recorded and used in the following equation:

$$q_r = \frac{k_r A_r (T_i - T_{i+1})}{L_r} \tag{1}$$

where

- q heat flux
- k thermal-conductivity coefficient (TC)
- A area of specimen face
- L thickness of specimen
- T temperature
- i subscript denoting reference surface
- r subscript denoting NBS reference sample

Since k and T were known for the NBS reference samples, their heat fluxes could be calculated. The heat flux of the test specimen was assumed to equal the average heat flux of the NBS reference samples.

$$q_s = \frac{q_{r1} + q_{r2}}{2} \tag{2}$$

where the subscript s denotes test specimen.

With the specimen heat flux known, the specimen TC was calculated by solving equation (3) for k_s.

$$k_s = \frac{q_s L_s}{A_s (T_i - T_{i+1})} \tag{3}$$

A sample calculation is shown in the appendix. After the TC at a given temperature was determined, the column temperature was raised and the TC at a higher temperature was determined. This procedure was continued until a curve of TC versus temperature was obtained.

To reduce data scatter due to oxidation at the interfaces in the column, the experiment was conducted twice. The first time, the experiment was run starting at low temperature and proceeding to high temperature. Then the column was disassembled and the interfaces were cleaned. After reassembly the experiment was run a second time, starting at high temperature and proceeding to low temperature. If there was a discrepancy in these curves due to oxidation, the high-temperature data from the second run and the low-temperature data from the first run were considered to be the accurate data. At the low temperatures used in this investigation, this precaution was not necessary for homogeneous, oxidation-resistant metal samples, such as FeCrAlY or Alloy-3; but it was necessary for TFRS composites, in which the tungsten fibers were exposed at the surface. To determine the TC of materials at higher temperatures, where oxidation would be more likely, the experiment should be performed in an enclosure containing a protective atmosphere. The copper spacers could be replaced with stainless-steel spacers to raise the operating temperature to approximately 1400 K, the calibration limit of the standard NBS reference material.

RESULTS

The experimental results obtained in this investigation are tabulated in table I and are illustrated graphically in figure 4. The TC of longitudinally reinforced TFRS was determined on a composite sample with Alloy-3 as a matrix. The sample contained approximately 65 volume percent of tungsten fibers and was 0.381 centimeter thick. The TC of this composite specimen varied quadratically with temperature from 79.5 watts per meter kelvin (W/m·K) at 600 K to 75.0 W/m·K at 900 K, according to the equation:

$$k_c = 6.16\times10^{-5}\ T^2 - 0.106\ T + 121 \tag{4}$$

where the subscript c denotes composite.

These data were used to calculate the longitudinal TC of the tungsten fiber itself. This was necessary because there are no published data for small-diameter tungsten fibers. The TC was determined for a 0.381-centimeter-thick unreinforced Alloy-3 matrix specimen. The TC of Alloy-3 varied linearly with temperature from 11.5 W/m·K at 500 K to 19.5 W/m·K at 900 K.

The other samples considered in this investigation simulated the thin sides of an air-cooled turbine blade. The TC of a 0.104-centimeter-thick FeCrAlY matrix specimen

was very similar to that of Alloy-3. The FeCrAlY TC varied linearly with temperature from 12.5 W/m · K at 500 K to 19.5 W/m · K at 900 K. The transverse TC of a W/FeCrAlY composite was determined on a specimen 0.127 centimeter thick. Its TC varied linearly with temperature from 26 W/m · K at 500 K to 44 W/m · K at 900 K. Longitudinal TC determinations of the TFRS with the FeCrAlY matrix and transverse TC determinations on the TFRS with the Alloy-3 matrix were not performed.

We determined the accuracy of the experimental procedure by measuring the TC for a sample of the NBS stainless-steel reference material. This measured TC varied linearly from 17.4 W/m · K at 500 K to 23.0 W/m · K at 900 K. This TC variation with temperature (fig. 5) was within 10 percent of the TC-versus-temperature calibration curve supplied by NBS.

DISCUSSION

To increase confidence in the experimental data and to demonstrate the reliability of this TC measurement procedure, two direct comparisons were made. First, the measured TC data of the stainless-steel standard were compared with the TC-versus-temperature curve supplied by NBS. Second, the experimentally measured transverse TC of a typical TFRS material was compared with the calculated TC for that material. The first comparison has already been described and is shown in figure 5. The agreement was very good and well within the approximately 10 percent error found in many TC measurement techniques (ref. 5). The second comparison was made to increase the confidence level in this experimental TC measurement technique.

Several analytical approaches to calculating the transverse TC in a unidirectionally reinforced composite material are reported in references 6 to 9. The thermal model method (eq. (7) of ref. 6) is reasonably accurate according to the data in that reference. Calculating TC with this model and equation requires TC data for the reinforcing fiber and the matrix material. The TC data for FeCrAlY were used, but the TC for the fiber was not measured directly. It was calculated from undirectional composite data. The longitudinal TC for a fiber composite was given by a rule-of-mixtures relation (ref. 6).

$$k = k_m V_m + k_f V_f \tag{5}$$

where

V volume fraction of component contained in composite

f subscript denoting fiber

m subscript denoting matrix

From the TC data for the longitudinally reinforced W/Alloy-3 composite and the TC of the Alloy-3 matrix, equation (5) can readily be solved for the TC of the reinforcing tungsten fiber. The calculated longitudinal TC for the reinforcing fiber (218CS tungsten) was plotted against temperature (fig. 6), along with the calculated unalloyed, longitudinal TC for annealed tungsten (ref. 10) and the estimated longitudinal TC for high-strength tungsten alloy wire (ref. 11). The calculated longitudinal TC for the 218CS tungsten wire varied quadratically with temperature from 122.5 W/m·K at 500 K to 105.5 W/m·K at 900 K and followed the relation

$$k = 9.36\times10^{-5}\ T^2 - 0.173\ T + 185.7 \tag{6}$$

Thus, the calculated longitudinal TC for the 218CS tungsten wire was approximately 20 percent lower than the estimated TC for an unalloyed, annealed tungsten wire and fell in the midrange between the unalloyed, annealed tungsten and the high-strength tungsten alloy wire. This calculated TC relationship was in the expected range, and we believe it to be an accurate representation. It is assumed that the TC's for 218CS and $W\text{-}1ThO_2$ are the same. In using longitudinal fiber TC data to help estimate transverse composite TC, we assumed that the fibers were isotropic with respect to TC. Therefore, the calculated longitudinal fiber TC was used to calculate the transverse TC of the FeCrAlY TFRS composite.

Reference 6 states that, to calculate the transverse TC, the following assumptions must be made: (1) that the composite is macroscopically homogeneous, (2) that locally both the matrix and the fibers are homogeneous and istropic, (3) that the contact resistance between the fiber and the matrix is negligible, (4) that the problem is two dimensional (i.e., that the temperature distribution is independent of the z-axis, which is parallel to the fiber axis), and (5) that the fibers are arranged in a rectangular array. However, some of these assumptions may not apply exactly for the FeCrAlY TFRS composite. For instance, since the tungsten fibers were highly worked, their properties were not completely isotropic. In addition, the fibers were not in an exactly square array because the fabrication process was not perfectly controlled. Bearing in mind these exceptions, we can use the following relation to calculate the transverse TC for composite materials:

$$k_t = k_m\left(1 - 2\sqrt{\frac{v_f}{\pi}}\right) + \frac{k_m}{B}\times\left(\pi - \frac{4}{\sqrt{1 - \frac{B^2 v_f}{\pi}}}\tan^{-1}\frac{\sqrt{1 - \frac{B^2 v_f}{\pi}}}{1 + B\sqrt{\frac{v_f}{\pi}}}\right) \tag{7}$$

where

$$B \equiv 2\left(\frac{k_m}{k_f} - 1\right)$$

and t is a subscript denoting transverse properties.

This relation tends to give calculated values slightly lower than the measured values, according to reference 6. The data from this calculation, along with the experimentally determined transverse TC for the TFRS materials, are plotted in figure 7. The calculated transverse TC ranged from 28 W/m·K at 500 K to 38 W/m·K at 900 K. Considering its approximate nature, this calculated TC relation with temperature compares reasonably well with the experimentally determined data, as shown in figure 7. The calculated values, over the temperature range considered herein, are generally within 10 percent of the data. The agreement of the experimental data and the calculated TC curve reverifies the accuracy of the thermal-conductivity comparator method.

Once we know the TC for the tungsten fiber and the matrix material, we can use equations (5) and (7) to calculate composite TC in the longitudinal and transverse directions as a function of fiber content. The results are understood to be generally conservative, as mentioned previously. Figure 8 depicts the calculated relation among longitudinal TC, fiber content, and temperature for FeCrAlY TFRS composites. For comparison, the experimental data for the 65-volume-percent-W/Alloy-3 TFRS composite and data from the literature (ref. 12) for MAR-M200, a high-strength, nickel base alloy, are also plotted. The longitudinal TC of the 65-volume-percent-W/Alloy-3 TFRS specimen was 3 to 5 times greater than that of MAR-M200, depending on temperature. The increased TC may be significant in the design of turbine blades incorporating TFRS materials. The calculated transverse TC's of FeCrAlY TFRS composites are plotted in figure 9 as a function of fiber content and temperature. The experimental data for the 50-volume-percent-W/FeCrAlY TFRS composite and the literature data for MAR-M200 are also plotted in the same figure for comparison. The transverse TC for the 50-volume-percent-W/FeCrAlY TFRS composite was 1.5 to 2 times greater than that of MAR-M200, depending on temperature.

The TC's of TFRS materials were not as great in the transverse direction as in the longitudinal direction. But the advantage of TFRS over conventional superalloys can be more significant in transverse TC than in longitudinal TC, depending on the turbine blade cooling method used. Most of the heat removed by the cooling air in convection-cooled blades must pass through the walls of the blade (i.e., in the transverse direction of the composite material). Thus, even a small advantage in transverse TC can be significant. Equations that permit the evaluation of high-TC, high-strength TFRS composites in impingement-convection-cooled turbine blades are presented in reference 11. The reader with a deeper interest in TC as a design consideration for TFRS materials is re-

ferred to that reference. As indicated in reference 11, an increase of 150 to 200 kelvins in use-temperature over a conventional superalloy blade is possible with cooled TFRS blades.

SUMMARY OF RESULTS

The following results were obtained from this investigation into the thermal conductivity of TFRS composites:

1. A thermal comparator method was developed to determine the TC of high-conductivity, thin-sheet samples. This method produced TC data that compared within 10 percent of a National Bureau of Standards sample calibration.

2. The transverse TC of the 50-volume-percent-tungsten/FeCrAlY TFRS composite was 1.5 to 2 times greater than the TC of MAR-M200, a typical high-strength nickel-base superalloy. The transverse TC varied linearly from 26 watts per meter kelvin (W/m·K) at 500 K to 44 W/m·K at 900 K.

3. The TC of the FeCrAlY matrix alloy, as determined by the comparator, varied linearly from 12.5 W/m·K at 500 K to 19.5 W/m·K at 900 K.

4. The longitudinal TC of the 65-volume-percent-tungsten/Alloy-3 TFRS composite was 3 to 5 times greater than the TC of MAR-M200, depending on the temperature. The longitudinal TC, measured parallel with the fibers, ranged from 79.6 W/m·K at 600 K to 75.5 W/m·K at 900 K. The TC varied with temperature according to the quadratic equation

$$k_c = 6.16\times10^{-5}\,T^2 - 0.106\,T + 121$$

where k is the TC coefficient, T is temperature, and the subscript c denotes composite.

5. The TC of the Alloy-3 matrix was similar to that of FeCrAlY and varied linearly from 11.5 W/m·K at 500 K to 19.5 W/m·K at 900 K.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 15, 1979,
505-01.

APPENDIX - SAMPLE CALCULATION

NBS stainless-steel reference (area, 1.267×10^{-4} m^2; thickness, 1.04×10^{-3} m)

$T_1 = 755.5$ K

$T_2 = 744.6$ K

$\Delta T_1 = 10.9$ kelvins

$$q_{r1} = k_{r1} \frac{1.267\times10^{-4}\ m^2}{1.04\times10^{-3}\ m} 10.9\ K$$

$k_{r1} = 21.18$ W/m·K at 750.1 K

$q_{r1} = 21.18\ (1.328)$ W

$q_{r1} = 28.12$ W

Test specimen (NBS material[1]: area, 1.267×10^{-4} m^2; thickness, 1.14×10^{-3} m)

$T_3 = 693.5$ K

$T_4 = 683.7$ K

$\Delta T_2 = 9.8$ kelvins

$$q = k \frac{\text{Area}}{\text{Thickness}} \Delta T$$

$$q_s = k_s \frac{1.267\times10^{-4}\ m^2}{1.14\times10^{-3}\ m} 9.8\ K$$

$k_s = q_s/1.089$ m·K

$$q_s = \frac{q_{r1} + q_{r3}}{2}\ (\text{eq. (2)})$$

$$q_s = \frac{28.12 + 19.39}{2}$$

$q_s = 23.76$ W

$$k_s = \frac{23.76}{1.089}\ W/m\cdot K$$

$k_s = 21.81$ W/m·K at 688.6 K

NBS stainless-steel reference (area, 1.267×10^{-4} m^2; thickness, 1.05×10^{-3} m)

$T_5 = 592.4$ K

$T_6 = 584$ K

$\Delta T_3 = 8.4$ kelvins

Equation (1)

$$q_{r2} = k_{r2} \frac{1.267\times10^{-4}\ m^2}{1.05\times10^{-3}\ m} 8.4\ K$$

$k_{r2} = 19.13$ W/m·K at 588.2 K

$q_{r2} = 19.13\ (1.0136)$ W

$q_{r2} = 19.39$ W

[1]Actual NBS reference value, 20.88 W/m·K at 689 K.

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TABLE I. - THERMAL-CONDUCTIVITY DATA

Material	Temperature, K	Conductivity, W/m·K
Alloy-3	566	12.7
	684	14.9
	768	16.2
	778	17.1
	834	18.4
	836	17.4
	889	20.1
	893	20.0
FeCrAlY	493	12.2
	496	12.8
	557	12.5
	594	14.1
	599	13.8
	663	15.2
	669	15.4
	679	16.1
	685	15.1
	710	16.8
	714	16.3
	725	16.9
	771	17.3
	771	17.0
	862	19.3
	873	18.6
NBS stainless-steel reference sample (measured in this study)	529	18.3
	614	20.4
	689	21.8
	761	22.4
	767	22.0
	797	22.5
	928	23.4
	934	22.8
Alloy-3/65-vol % W TFRS	600	78.6
	605	80.0
	686	77.3
	690	76.5
	798	75.0
	807	75.6
	893	75.1
	907	75.1
FeCrAlY/50-vol % W TFRS	514	27.0
	514	27.7
	618	30.6
	618	31.6
	698	34.4
	746	38.0
	749	38.8
	782	39.3
	785	40.6
	854	40.6
NBS stainless-steel reference calibration (supplied by NBS)	400	16.2
	450	17.1
	500	17.9
	600	19.3
	700	20.6
	800	21.9
	900	23.0
	1000	24.1

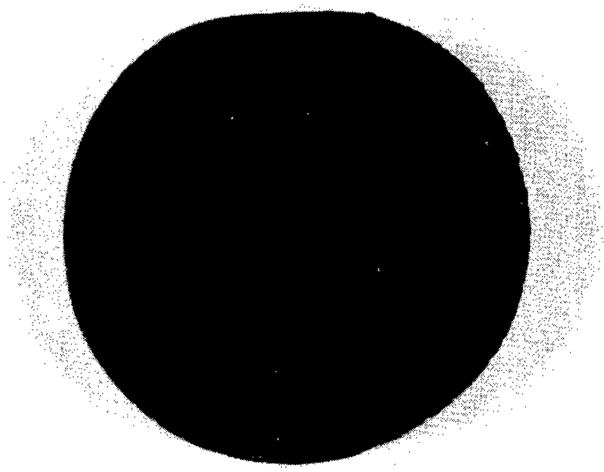

Figure 1. - Transverse W/FeCrAlY thermal-conductivity specimen. ×5.

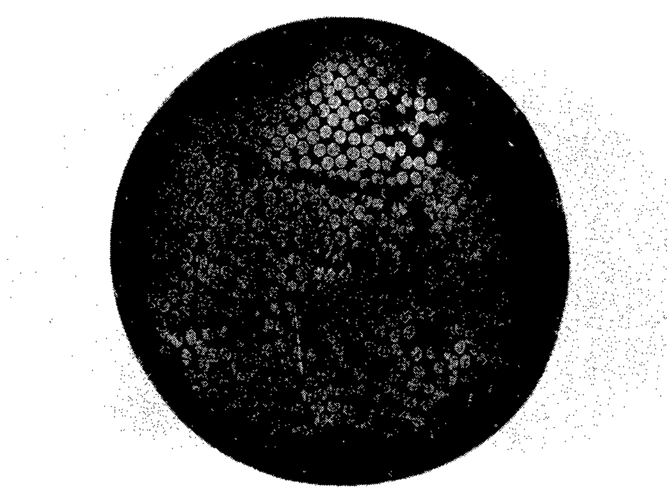

Figure 2. - Longitudinal W/Alloy-3 thermal-conductivity specimen. ×5.

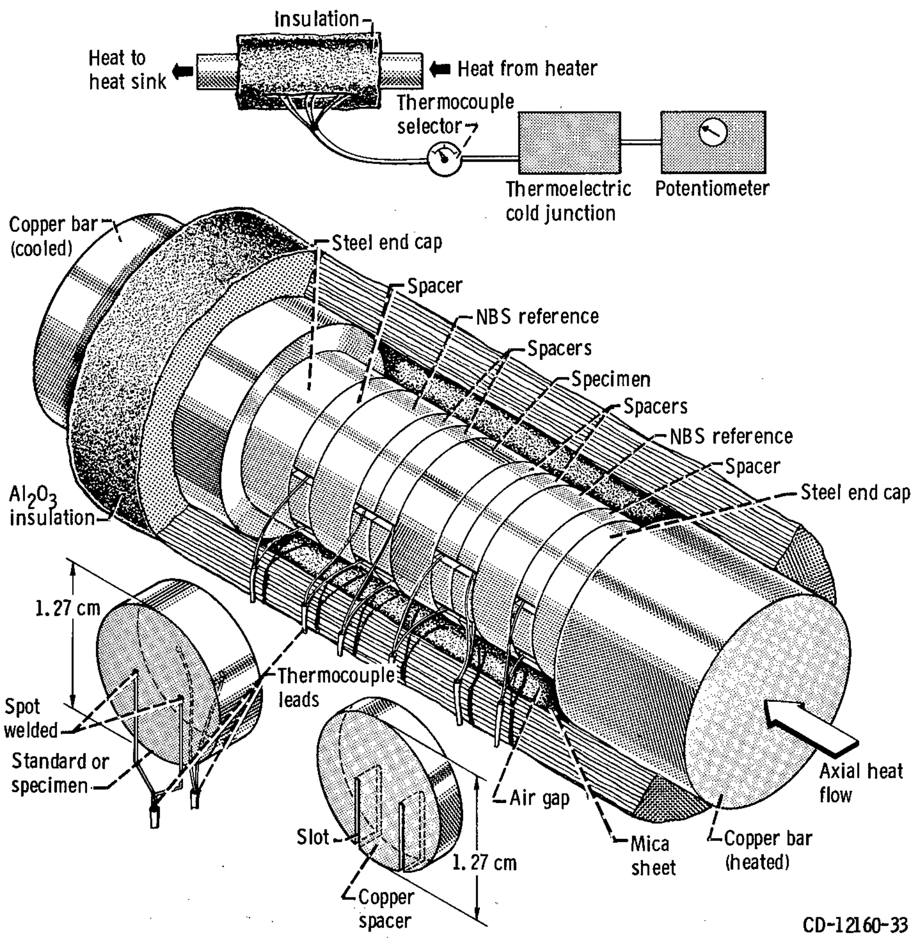

Figure 3. - Thermal-conductivity measurement apparatus. Heat passes through NBS reference samples and the specimen between them. (Precision thermocouple thermoelectric cold junction and potentiometer are used to determine temperatures. Force is applied to each end of assembly during TC determination.)

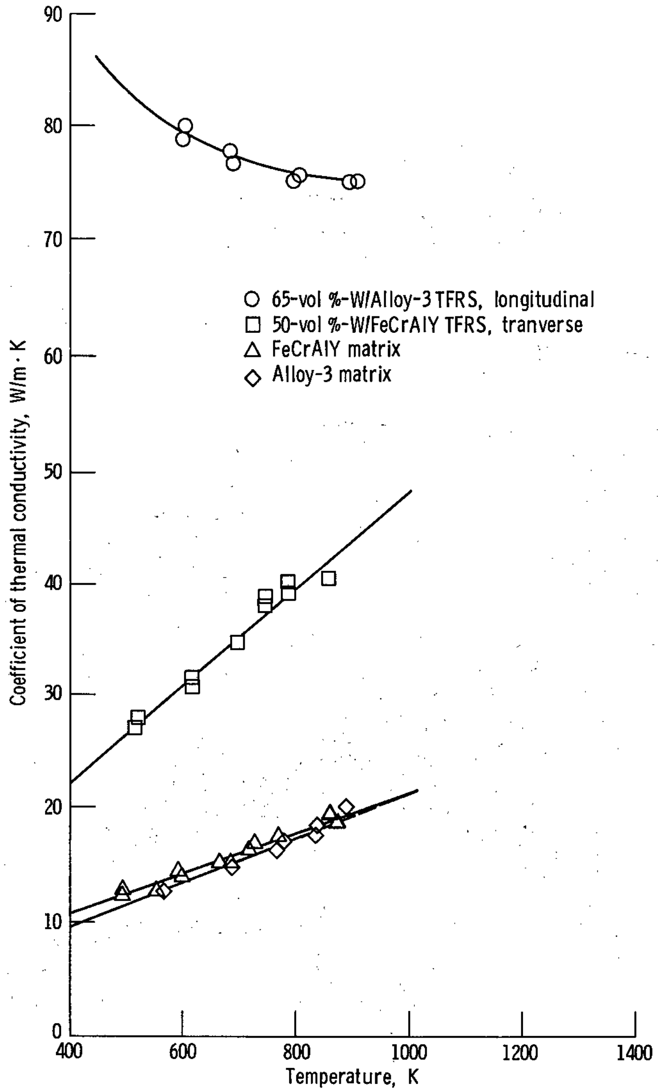

Figure 4. - Thermal conductivity as determined for selected materials over a range of temperatures by using a high-temperature thermal-conductivity comparator.

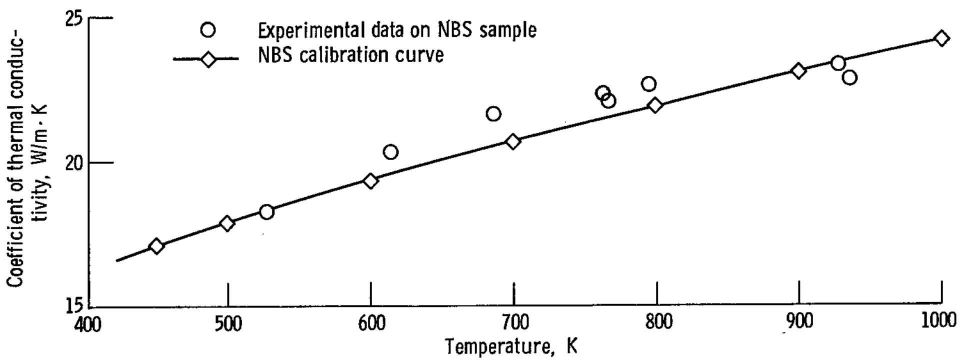

Figure 5. - Experimentally determined thermal conductivity of National Bureau of Standards sample as compared with data supplied by National Bureau of Standards, over a range of temperatures.

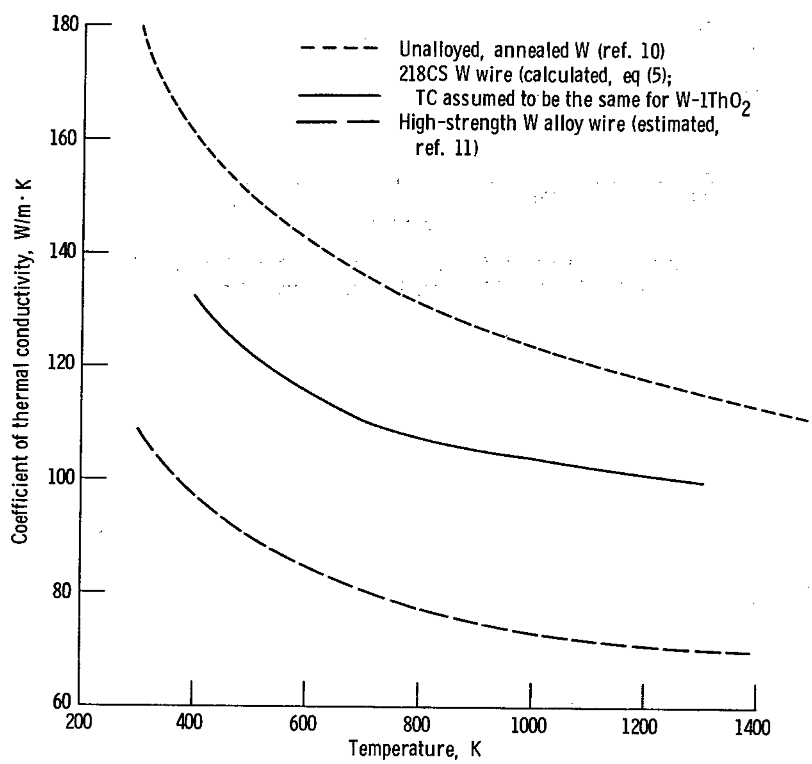

Figure 6. - Calculated thermal conductivity of 218CS W and W-1ThO$_2$ wire compared with estimated (method of ref. 11) TC of high-strength, annealed tungsten wire.

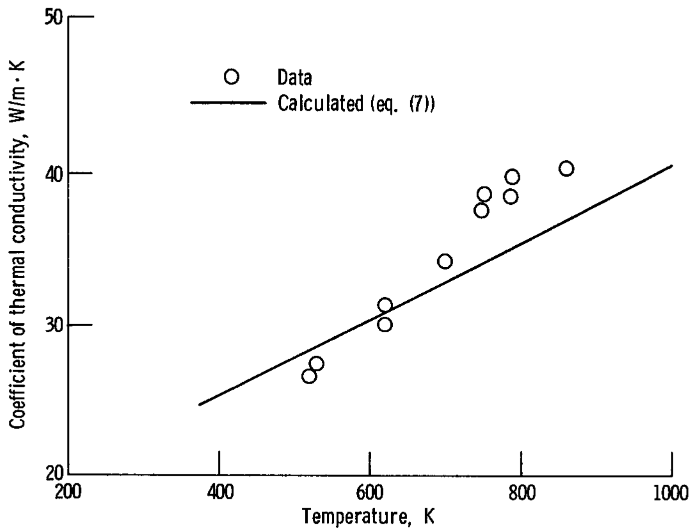

Figure 7. - Measured and calculated transverse thermal conductivity of 50-vol %-W/FeCrAlY TFRS composite over a range of temperatures.

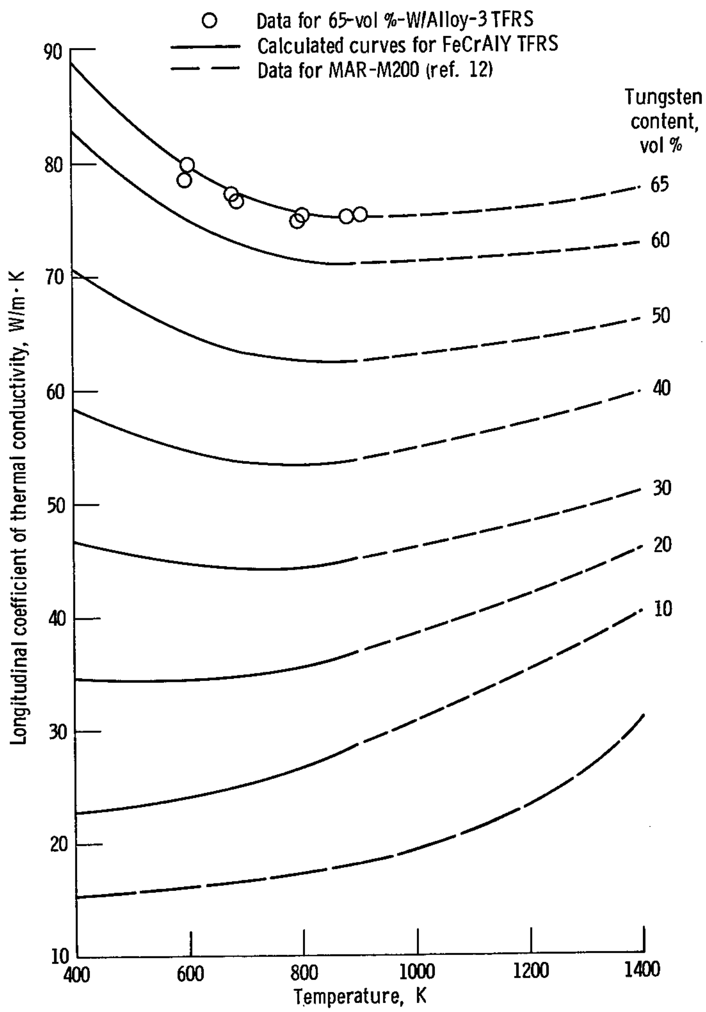

Figure 8. - Calculated longitudinal thermal conductivity of FeCrAlY TFRS composite, as it varies with fiber content and temperature, compared with experimental data for 65-vol %-W/Alloy-3 TFRS and data for MAR-M200 (ref. 12).

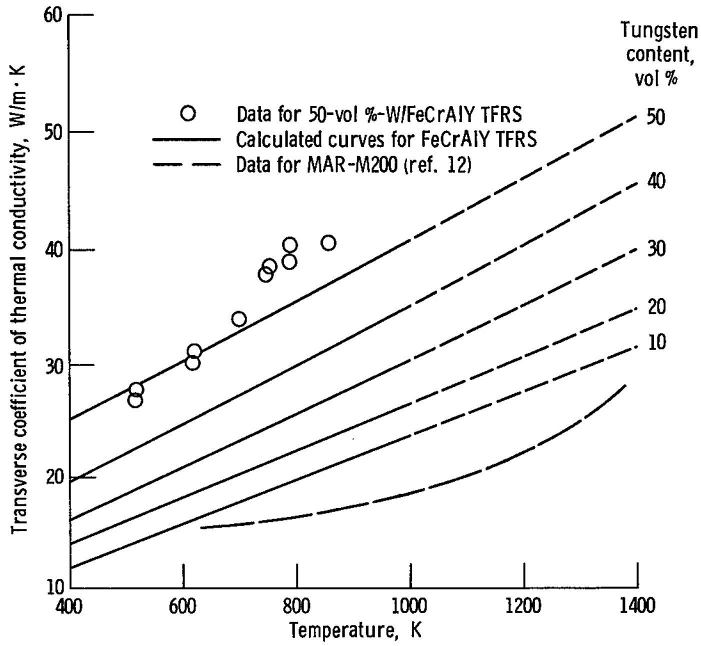

Figure 9. - Calculated transverse thermal conductivity of FeCrAlY TFRS composite, as it varies with fiber content and temperature, compared with experimental data for 50-vol %-W/FeCrAlY TFRS and data for MAR-M200 (ref. 12).

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16. Abstract

The thermal conductivity (TC) of tungsten-fiber-reinforced superalloys was determined for two composite systems by using a thermal conductivity standard from the National Bureau of Standards and a comparator and technique developed for that purpose. The results were compared with TC data for the nickel-base alloy MAR-M200. The technique lends itself to applications involving thin specimens, such as thin-walled turbine blades. The TC's of the composite systems were considerably higher in both the longitudinal and transverse directions than that of the monolithic superalloys used as the matrices.

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